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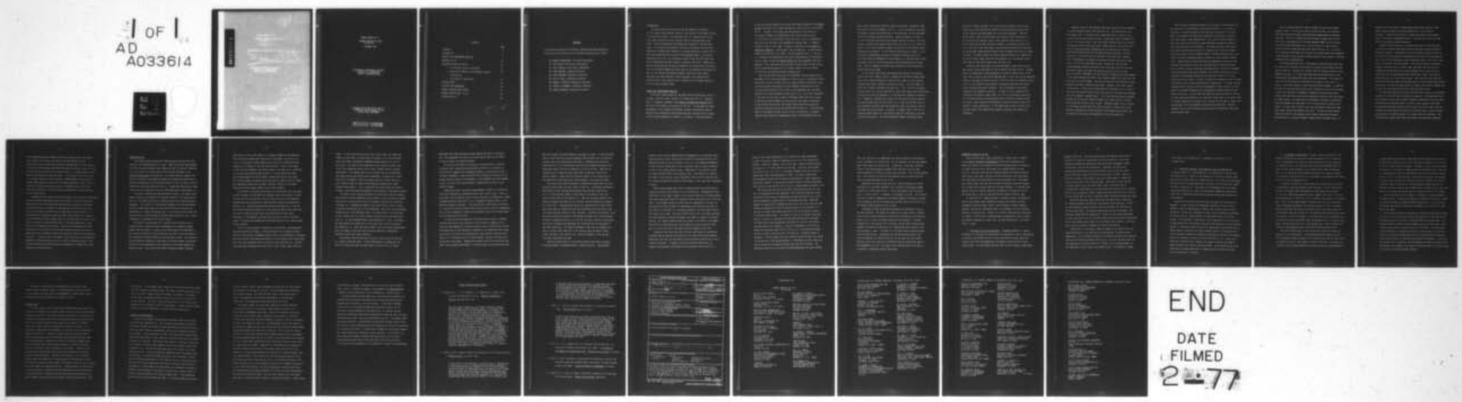

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DEPARTMENT OF ATMOSPHERIC SCIENCES
UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

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DEPARTMENT OF ATMOSPHERIC SCIENCES
UNIVERSITY OF WASHINGTON
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CONTENTS

PERSONNEL

The following scientific and technical personnel have been employed by the Contract during part or all of the period covered by this report:

DR. NORBERT UNTERSTEINER, Principal Investigator

DR. GARY MAYKUT, Co-Principal Investigator

DR. SEELYE MARTIN, Co-Principal Investigator

DR. THOMAS GRENFELL, Research Associate

MR. PETER KAUFFMAN, Electronics Technician

MR. FRED A. RIGBY, Predoctoral Associate

MR. DONALD K. PEROVICH, Predoctoral Associate

MR. TERREN M. NIEDRAUER, Predoctoral Associate

MR. EDWARD JOSBERGER, Predoctoral Associate

INTRODUCTION

During the past year we have carried out theoretical studies on: (i) the regional heat and mass balance of the ice pack in the Central Arctic, (ii) radiative transfer in ice and snow, and (iii) internal waves in the mixed layer resulting from the combined effects of many pressure ridge keels. Field and laboratory experiments were conducted in the following areas: (i) ablation of horizontal, vertical, and sloping ice walls with a temperature slightly above freezing, (ii) growth mechanisms in young ice in both undisturbed water and in water with propagating waves, (iii) optical properties of sea ice, (iv) stationary internal waves near the pycnocline, and (v) temperature and mass changes in pressure ridge keels. Papers have been written describing the optical properties of ice and snow in the Arctic Basin, the energy exchange over young sea ice, the thickness distribution of sea ice, the laminar and turbulent boundary layer which forms under a horizontal ice sheet floating on warm salty water, the application of satellite data in the testing of sea ice models, and the summer evolution of a first-year pressure ridge.

DYNAMIC AND THERMODYNAMIC MODELING

During this reporting period, two papers were published and a third is in press. The first paper, written in collaboration with A. S. Thorndike and D. A. Rothrock, appeared in the Journal of Geophysical Research under the title "The Thickness Distribution of Sea Ice". It described the formal development of the thickness distribution concepts and presented results derived from climatological heat balance data and a two year strain history of the triangle formed by T-3, ARLIS II, and NP-10. A detailed analysis

of how ice thickness affects the surface heat balance appeared in the AIDJEX Bulletin under the title "Energy Exchange over Young Sea Ice in the Central Arctic". Included in this paper were descriptions of the effects of: (i) seasonal changes in the magnitude of the incident energy fluxes, (ii) variations in the thickness of the snow cover, and (iii) temperature departures from the norm in the atmospheric boundary layer. A somewhat expanded version of this paper is ready for submission to the Journal of Geophysical Research. A third paper ("Sea Ice Modeling: Its Testing with LANDSAT and Potential Use in FGGE"), written together with R. T. Hall and D. A. Rothrock, was presented at the annual COSPAR meeting in Philadelphia and will appear in both the AIDJEX Bulletin and the proceedings from that symposium. This paper describes the extent to which satellite data can be used to judge the performance of ice models, measure the ice thickness distribution, and estimate regional exchange rates.

Much of the effort during the last few months has been devoted to an assessment of the large-scale behavior of the ice pack in the Central Arctic. Because the ice pack is made up of ice of many different thicknesses, each of which responds differently to similar thermal and mechanical forcing, the large-scale effects of the ice pack on the atmosphere and ocean must depend on the relative amounts of each type of ice. Of critical importance is the young ice less than a meter in thickness, where the rates of mass production and heat exchange can vary by one to two orders of magnitude. At the present time we know little about large-scale effects primarily because we lack hard data on the distribution of young ice. Direct measurements of the amount of young ice are, as yet, not feasible - available submarine sonar data do not adequately resolve ice thicknesses below one

meter, while airborne and satellite sensors are severely limited by clouds and provide only brief glimpses of the ice. Lack of information regarding the amount of young ice provided much of the motivation for the development of the ice thickness distribution model. With this model we are able to utilize strain data derived from the observed motions of buoys or drifting stations, together with measured heat fluxes over thick ice, to predict the amount of ice in any thickness category on the basis of our physical understanding of ice behavior. If the thickness distribution is known, it is a relatively straightforward procedure to calculate regional totals for quantities which are dependent on ice thickness, e.g. turbulent heat fluxes, ice growth, salt flux to the mixed layer, and solar heating of the upper ocean. Work is underway to estimate these quantities from available heat balance and position data.

In our initial calculations we combined the thickness distribution results from the T-3/ARLIS II/NP-10 triangle with the heat transfer model used in the "Energy Exchange over Young Sea Ice" paper to study regional exchange rates under a variety of winter conditions. While the amount of young ice in these calculations was small (0.1 - 0.5% in the 0-10 category and only about 2.5% thinner than 40 cm), large-scale totals were significantly different than would be expected if all the pack were composed of perennial ice. Frequently, turbulent heat losses over the young ice nearly balanced the sensible heat gain over the thicker ice, so that the net heat input to the atmospheric boundary layer was essentially zero; occasionally, the net heat input was even positive. In general, it appears that if the 0-10 cm category exceeds about 0.5%, the boundary layer will experience a net heat gain from the surface. So, while traditional methods would predict the

heat flux to remain constant, it is not only quite variable, but can also change sign, affecting both the stability of the planetary boundary layer and the momentum exchange between the ice and the atmosphere. When the growth rates of young ice were taken into account in the calculations, it was found that the regional rates of mass production were typically 2-2½ times larger than had been previously assumed. To estimate the total salt flux at the top of the mixed layer, we used partition coefficients reported by Cox and Weeks (CRREL Research Report 345) and growth rates from our simple ice model. We found average salt fluxes under the thinner ice categories to be 10 to 50 times larger than under the perennial ice, and regional totals which were at least double those under the thick ice.

Recently, the calculations have been extended to cover the entire two year period, and we have begun to look at monthly and annual totals. Average annual ice production in the undeformed ice within the region was 63 cm/cm^2 year, being 55 cm/cm^2 year during 1962/1963 and 71 cm/cm^2 year during 1963/1964. Almost all the net ice growth occurred in the first-year ice categories; there was little net growth in the perennial ice because summer ablation almost exactly balanced the winter accretion. The ice produced in the thinner categories was consumed in two ways: (i) some of it was crunched up and converted into pressure ridges, while (ii) the rest contributed indirectly to ice export because the area defined by the 3 stations increased during the period. Mass losses by the deformed ice were not directly taken into account in these calculations. In the coming year, we plan to carry out a detailed study of how these effects combine to balance the regional ice production.

Regional values of the turbulent heat fluxes were also quite different from those measured locally over the thick ice. The sensible heat flux, for example, was -1.1 kcal/cm^2 year, rather than the +2.7 kcal/cm^2 year usually given for the central ice pack. Latent heat losses increased from -3.2 to -3.8 kcal/cm^2 year. Thus, the annual turbulent heat loss from the ice pack was about -5.0 kcal/cm^2 year, rather than the -0.5 kcal/cm^2 year which is obtained without consideration of the thickness distribution. Short-wave radiation input to the ocean was also calculated. We found that about 1.8 kcal/cm^2 year was absorbed in the ocean below 3 meters; this is comparable to estimates of the amount of heat reaching the underside of the ice from the Atlantic layer. We now feel (see Pressure Ridge Morphology section) that much of the short-wave radiation absorbed below the 3 meter level goes into melting ice which was at one time part of pressure ridge keels, but the picture is complicated by what happens to the false bottoms which form at the interface between the fresh water and salt water during the summer. The ocean also absorbs large amounts of solar energy in the upper 3 meters of open leads. Because of the stable summer stratification, little of this energy makes its way under the ice, instead most goes into lateral melting of the lead walls and increased heat exchange with the atmospheric boundary layer. If all the short-wave energy absorbed between the surface and 3 meters had gone into lateral melting, it would have melted away 10-15% of the ice pack. Although probably only a fraction of this energy actually went into lateral melting, it does point up the potential importance of lateral melting in the regional mass balance, and the need for field studies to determine its role more precisely.

One of the most interesting results of this study is that the heat and mass balance over intermediate ice thicknesses (20-80 cm) is at least as important, if not more important, than that over either thick ice or open water. For example, the annual mass production in the 40-80 cm category was roughly equal to the combined total in all other thickness categories. Also, heat losses in the 20-80 cm range frequently exceeded the combined totals from all other ice thicknesses. This means that even models which treat both the open water and thick ice ignore much of the heat exchange. The strain history of the T-3/ARLIS II/NP-10 triangle indicates that we can expect relatively large year-to-year variability in the regional exchange rates. Annual totals of quantities which are especially sensitive to the thickness distribution (such as the ice production and the sensible heat flux) varied by a factor of two over the study period. Because ice movement during the two years was quite different, this factor of two may be a good estimate of the expected variability, but the strain record is not long enough to tell for certain. Finally, it should be stressed that the thickness distributions used in this study were quite conservative. In places like the Transpolar Drift Stream or near the free-boundary of the ice pack, we expect there to be greater divergence and correspondingly greater amounts of open water and thin ice. We also know from satellite data that there are periods, at least, when open water/thin ice cover much larger areas in the central pack - it has been reported, for example, that in March 1971 and again in March 1972 approximately 12% of the Beaufort and Chukchi Seas were open. Regional exchange rates in such situations would be orders of magnitude larger than those reported above.

We are currently working on ways to improve our ability to predict regional values. To aid in this effort, we plan to add to the thickness distribution model the simple heat balance/ice growth model we developed last year. This will eliminate the need to specify growth rates and will also give us the capability of allowing feedback between the heat balance and the thickness distribution, e.g. we will be able to treat directly lateral melting in leads and solar heat input below the ice. In the next set of regional calculations, we also plan to include several more categories in the multiyear ice to provide a clearer picture of mass changes in pressure ridges and thick undeformed ice.

The greatest uncertainties in the regional calculations performed thus far are due to limitations in our ability to resolve the thickness distribution of young ice. Because the T-3/ARLIS II/NP-10 triangle covered an area 600-800 km across, it is likely that there were periods when parts of the triangle were converging while other parts were diverging; if this were the case, the position data could indicate no net change of area, while, in reality, significant amounts of open water were being produced. In addition, the position data from these stations were reported only once every few days, so that short periods of convergence followed by divergence would again produce open water which could not be detected by looking at the area change. For these reasons, we suspect that the thickness distribution calculations predicted somewhat less open water/ thin ice than actually existed in the region. To check this we need to carry out calculations using strain data with greater spatial and temporal resolution. The data collected during AIDJEX are ideal for this purpose and we intend to determine thickness distributions on a variety of spatial scales within the AIDJEX array. In

preparation for this effort, AIDJEX meteorological data from April 1975-January 1976 were used to calculate growth rates for the young ice categories. Within the next couple of months, we expect to have growth rates for the entire experimental period. Positions and strain rate data are being processed by AIDJEX personnel.

Recently, AIDJEX data for a 20 day period in May 1975 have been used to calculate thickness distributions within the three triangles defined by the manned stations. The amount of ice in the 20-80 cm range was found to be similar to that obtained in the previous calculations, but the amount of ice in the 0-10 cm category was almost always much larger - up to 8% in some cases, with values of 3% being common. With this much young ice present, regional rates were up to 10 times larger than those over the thick ice. Although the period was one of strong divergence (up to 1% per day) and relatively slow ice growth (about 25% of the winter rates), the amount of open water/thin ice is surprisingly large. Until position data from other periods have been processed and analyzed, we do not know whether these results are typical. We view with some suspicion, however, the disparity between the earlier results and the smaller-scale (100 km) AIDJEX results.

At this point there has not been sufficient time to carry out a detailed analysis of the strain field components to determine if the predicted values are reasonable, but we have located a potential problem which can occur when the thickness distribution model is driven by high frequency strain data. We know that pure shear along non-linear cracks in the ice cover causes the formation of equal amounts of pressure ice and open water; further, we know that the shear is generally equal to or greater than the divergence. The thickness distribution model takes into account the open water production

and ridging generated by shearing motions, but does not take into account the direction of the shear, and therein lies the potential problem. If shear occurs along a particular direction, some open water will be produced; if the shear then reverses direction before new ice has had a chance to form, the area of open water will not increase further. The model, however, would predict the formation of more open water. It is possible that over periods of a few days shearing in the ice pack is characterized by back and forth motions along systems of cracks with the same orientation, in which case the model would generate too much open water. The AIDJEX strain fields have sufficient resolution in time to cause such effects and are being examined for this possibility.

Although there are several parts of the model (such as the ice redistributor and keel ablation) where we have had to use physical intuition rather than observational data, we believe that the most serious obstacle to obtaining accurate thickness distributions for the regional calculations lies not so much with the model as with the strain rates used to drive the model. As mentioned above, large space scales and crude time resolution will cause us to underestimate the thin ice/open water; on the other hand, very small space scales can lead to erroneous strain rates in situations where most of the strain occurs along one or two cracks. We plan to collaborate with AIDJEX investigators in an effort to utilize existing position data from buoys and manned stations to determine optimal space and time scales for the estimation of strains. It may turn out, for example, that three points are not generally adequate to calculate average strains, at least on some space scales. Such information would affect the spacing and configuration of future buoy arrays planned for the Arctic Ocean.

RADIATION IN ICE

The primary activity during this reporting period has been the final reduction and interpretation of T-3 data. These results have been combined with those obtained at Barrow into a paper entitled "The Optical Properties of Ice and Snow in the Arctic Basin" which has been submitted to the Journal of Glaciology for publication. This paper describes temporal and spatial variations in the spectral albedos and attenuation coefficients of the major categories of ice in the Arctic Basin, as well as data on vertical attenuation and scattering within the ice. A paper describing some of these results was also presented at the spring AGU Conference in Washington, D. C.

The results indicate that the magnitude and shape of the albedo curves depend strongly on the amount of liquid water present in the upper part of the ice. The albedo of dry snow is high and shows only a weak wavelength dependence. This result is in substantial agreement with the observations of Mellor (1965) whose curves for new snow and melting snow bracket our measurements for heavy, wind-packed snow. In the case of melting snow, the albedo exhibits a definite spectral gradient above 650-700 nm, but is again independent of wavelength in the visible region.

The albedo of pond-covered ice is spatially quite variable, but is characterized by a maximum at short wavelengths and a dramatic decrease between 500 nm and 800 nm. Values at short wavelengths are determined by the scattering properties of the underlying ice, while values above 800 nm are determined by Fresnel reflection from the water surface. The transition zone (500-800 nm) represents a region where the albedo becomes increasingly insensitive to the underlying ice as absorption by the water becomes the dominant effect. Thus, most of the albedo difference between individual

ponds occurs in the visible where it is readily apparent to the naked eye. The highest pond albedos were found early in the season on multiyear ice. The ice in such ponds usually appeared to be whitish or cloudy due to the presence of air bubbles in the near-surface layers. Later in the season, as the melt ponds deepened, the albedos tended to be lower due to increasing brine volume and decreasing bubble density. In areas where melt ponds persisted throughout the entire summer, internal melting was very large. Brine volumes beneath old ponds varied from 20% at a depth of 50 cm to about 55% immediately beneath the ice-water interface; except for open leads, these ponds had the lowest albedo of any surface examined.

In contrast to the ponds on multiyear ice, the shallow, dark blue ponds on the first-year ice near Barrow all appeared to be quite similar in color. The high salinity and relative clarity of the first-year ice yielded pond albedos which were substantially lower than those typically encountered on multiyear ice. Because the Barrow observations were made early in the melt season before appreciable amounts of solar energy had been stored within the ice, brine volumes were lower than those beneath the old melt ponds. Presumably, if measurements could have been carried out later in the melt season, first-year pond albedos would have been essentially the same as those of the old ponds.

Bare ice albedos spanned a range which, to some extent, overlapped both the snow and melt pond albedos. Melting multiyear ice is typically bluish-white in color and has a decomposed surface layer a few centimeters in thickness. This layer results from enhanced absorption of solar radiation near the surface, and its optical properties differ from those of the underlying ice. Observations were made to determine how variations in this surface layer affect the

albedc. It was found that the thicker the surface layer, the higher the albedo; for the range in surface layer thicknesses (2-15 cm) encountered during the summer, wavelength independent albedo changes of up to 0.10 were noted. The albedo of the underlying ice was found to be lower than that of the decomposed surface, and to have a steeper spectral gradient above 600 nm. For example, when an 8 cm surface layer was scraped away, the albedo decrease was 0.05 at short wavelengths, increasing to a difference of 0.10 at 1000 nm. When the surface layer was frozen, there was a small albedo increase at shorter wavelengths and progressively larger increases above 600 nm. This is consistent with other observations which indicate a decreasing spectral dependence with decreasing liquid water content.

Two types of bare ice were observed near Barrow during the melt season: blue ice which closely resembled the melt ponds in color, and white ice which consisted of a drained layer 5-10 cm in thickness, underlain by clear blue first-year ice. Although the albedo of this white ice was similar to that of the melting multiyear ice at long wavelengths, there was a large difference between the two in the 400-600 nm band. The lower albedo of the first-year ice was primarily due to a smaller amount of backscatter by the underlying blue ice. At long wavelengths where light penetration is small, the albedo was determined by the properties of the surface layer and not by those of the underlying ice. Thus, the surface layers on the first-year and multiyear white ice appear to have had similar optical properties, although the underlying layers were rather different.

The albedo of the blue melting first-year ice was low due to the lack of a surface scattering layer. At short wavelengths its albedo was only about 0.10 larger than that of pond-covered first-year ice. At longer

wavelengths the albedo decrease was more gradual than that of the ponds, but it too approached the Fresnel limit near 1000 nm where the influence of the thin water film became important.

As a check of the overall consistency of the observations, spectral irradiances were integrated over wavelength to obtain a bulk albedo (α_s) which could be compared with independent albedos (α_k) measured with Kipp and Zonen radiometers. When corrections were introduced to account for the greater spectral range of the radiometers, close agreement was found between α_s and α_k on both clear and cloudy days, supporting the accuracy of the spectral albedos.

Interpreting total transmission measurements in terms of an extinction coefficient represents an averaging process over a finite layer. Since, in many cases, sea ice exhibits large vertical variations in attenuation, a depth averaged extinction coefficient is not a fundamental property which can be applied to general situations. For the extinction coefficients to be useful in a predictive sense the regions they describe must be relatively homogeneous. Thus, we have attempted to identify the important layers and ice types whose optical properties are distinct.

To study the optical properties of the near-surface layers, intensity profiles were taken in the snow and in the ice down to a depth of 50 cm. While the snow appeared to be optically quite uniform, melting white ice was characterized by a rapid decrease in attenuation with depth near the surface. The surface of the white ice consisted of a loose granular layer which was about 5 cm in thickness early in the melt season, increasing to about 10 cm by the end of the summer. Beneath this granular layer was a transition zone where the ice became consolidated. In the multiyear ice the transition zone

was usually about the same thickness as the granular layer. In the first-year white ice the transition zone was generally absent because the ice below the granular layer was saturated with melt water. Although brine volume and bubble density in the ice below the transition zone changed with depth, this change was gradual and the ice appeared to be fairly uniform. When the ice surface was at or below the local water table, a granular layer did not develop; however, a weak transition zone was present in the latter part of the summer due to the large brine volume gradient in the upper half meter.

The results show large differences in attenuation between the snow, the granular surface layer, and the interior of the ice. The greatest attenuation was observed in dry, wind-packed snow where the extinction coefficients (17 m^{-1} at 500 nm) were roughly 4 times those of the granular layer, and about 20 times those of the interior ice. When the snow began to melt, the density increased from about 0.4 to 0.5 gm/cm^3 and the attenuation decreased by a factor of 2. Although these results are representative of dense arctic snow, the values are probably smaller than those which would be found in the less dense snow more typical of lower latitudes. Extinction coefficients in all cases were relatively constant in the 400-550 nm region, but increased almost an order of magnitude by 750 nm. In the red, the rate at which the extinction coefficient increased with wavelength was correlated with the magnitude of the total attenuation. The spectral gradient in the snow, for example, was about 2.5 times larger than that in the granular layer and about 9 times larger than that in the interior ice. Spectral gradients in the two snow cases were essentially the same.

Extinction coefficients in the surface granular layer were calculated using both upward- and downward-looking intensity profiles. Both methods

yielded similar results, demonstrating the homogeneity of the granular layer. Below the granular layer the extinction coefficients decreased rapidly until reaching the interior ice at a depth of 12-15 cm. The wavelength dependence of the extinction coefficients in this transition layer was nearly identical to that in the surface granular layer. Attenuation in the interior ice was only about one-third that in the granular layer. The decrease of intensity with depth in the interior ice was logarithmic from 12-50 cm indicating that at a given wavelength the extinction coefficients in this layer were independent of depth.

Underice measurements were used in conjunction with the profile data to estimate extinction coefficients in the ice below 50 cm. Averaged extinction coefficients in the lower 2 meters of the ice were found to be slightly smaller than those immediately below the transition zone; differences of up to 10% were noted. The averaged extinction coefficients for homogeneous first-year ice calculated from total transmission measurements were about 25% less than in the interior of multiyear ice, presumably because of its lower bubble density and higher brine volume. Extinction coefficients in the ice beneath multiyear melt ponds generally decreased throughout the summer in response to internal melting. For example, beneath mature melt ponds in the middle of the summer the extinction coefficients were nearly identical to the values for first-year ice, but by the end of the summer they had dropped by about 25%.

Although we have found that the extinction coefficient at a particular wavelength may be constant with depth in an ice layer with uniform physical properties, this does not imply that the bulk extinction coefficient is also constant with depth. In general, the bulk extinction coefficient (κ_z) depends on the spectral distribution of the radiation field as well as κ_λ.

Because of the rapid attenuation of the radiation at longer wavelengths, κ_z drops as much as 2 orders of magnitude in the first 10 cm beneath the surface. Below this, however, it was found that κ_z does not change rapidly with depth nor is it very sensitive to ice type. A typical value between 10 and 100 cm for κ_z is 1.5 m^{-1} in excellent agreement with the results of Untersteiner (1961) and Chernigovskii (1966). Our results demonstrate that attenuation within the ice cannot be described by a single attenuation coefficient; however, if the surface scattering layer is treated separately, solar heating in the interior of the ice can be approximated using Beer's law.

The construction and initial testing of the cylindrical tank for the thin ice experiments has been completed. The cylindrical shape was chosen to minimize flexure induced leakage when the tank was being filled, and to simplify geometrical complications in interpreting the data. Additional geometrical complexities introduced by the finite size of the tank have been reduced considerably by using mirrored plexiglass for the tank walls, so that the ice sheet should behave optically like a plane parallel layer of infinite horizontal extent. Ice sheets up to 30 cm in thickness have been grown in a period of a few days with negligible thickening at the edges. The fiber optics coupling apparatus has been built, and its installation and calibration are in progress. A series of experiments on the optical properties and growth rates of thin saline ice is in the beginning stages. The work is being carried out by Mr. Don Perovich, a graduate student in Geophysics. The new digital FSK data recording system has been field tested in melting snow in the Cascade Mountains. Performance and data recovery of the new system are substantially better than with the old system. The operational amplifier in the profiling spectrophotometer has been replaced

with a new low noise, low temperature unit which increases the sensitivity of the instrument by a factor of 20. This is important for snow measurements where light levels can be quite low. In addition, turret-type irradiance plates of the type designed by Raymond Smith have been built for both spectrophotometers to replace the opal glass diffusers. The resulting improvement in the accuracy of irradiance measurements can be as much as 95% for clear sky conditions when the sun is low.

Observations of total albedo over thin, rapidly growing sea ice were obtained for us by AIDJEX personnel over a variety of thicknesses between 10 and 80 cm in the Central Arctic. Similar measurements were also made by Dr. S. Martin and Mr. P. Kauffman in the marginal ice zone. This information will be used for comparison with albedos measured over young ice grown in the laboratory and for evaluating more precisely the role of thin ice in the regional energy balance of the ice pack.

A photometric model to describe absorption and scattering in sea ice has been developed. The theory for scattering by large dielectric spheres was utilized to obtain absorption coefficients and scattering functions for bubbly ice as a function of bubble diameter and wavelength. Equivalent parameters for brine pockets will be derived from the same formalism which, together with Rayleigh scattering, will complete the specification of the basic photometric model. The model will be tested using transmission data from the freezing tank. Although we can now theoretically predict the optical properties of different types of ice and snow, we do not really know how closely the theoretical scattering functions approximate those of non-homogeneous real ice. Ice grown in the freezing tank will be used in experiments to determine how well they match.

LABORATORY STUDIES OF SEA ICE

During the past year a paper submitted by S. Martin and P. Kauffman to the Journal of Physical Oceanography entitled "An Experimental and Theoretical Study of the Turbulent Convection Generated under a Horizontal Ice Sheet Floating on Warm Salty Water" was accepted subject to minor revision. The paper describes the combined laminar and turbulent boundary layer which occurs under a melting ice block floating on warm salty water. This study models the bottom melting of sea and glacial ice in the summer Arctic which occurs when the solar radiation absorbed in leads and through the ice heats the sea water under the ice above freezing. Our results show that the onset of turbulent convection beneath the ice causes the ice to melt about twice as fast as predicted from the laminar diffusion case.

In other work, Mr. Edward Josberger, a graduate student, continued his work on the boundary layers adjacent to vertical and sloping ice walls suspended in warm sea water; and Mr. Terren Niedrauer, another graduate student, continued his laboratory study of the formation of brine drainage features in young sea ice. Finally, in a further investigation of young sea ice growth, S. Martin and P. Kauffman began an experimental study of grease and pancake ice growth in a wave field. We next discuss each of the above topics in detail.

1. The Ablation of Ice in the Ocean. A graduate student, Mr. Edward Josberger, is continuing his experimental and theoretical study of the ablation of vertical and slanted ice walls in warm salt water solutions, where the solution salinities and temperatures correspond to those of Arctic Ocean surface water. His experiments show that the ice melts through a complicated

boundary layer flow. This flow occurs because the thermal diffusivity of sea water is almost 10^3 greater than the salt diffusivity, so that the temperature disturbance generated by the melting wall propagates further from the wall than the salt disturbance. Therefore, the less-saline buoyant water generated by the melting remains close to the wall, while away from the wall, water of the far-field salinity is cooled. When the far-field salinity is less than 25 $^{o}/_{oo}$, this colder water is lighter and rises along with the inner less-salty water. When the far-field salinity is greater than 25 $^{o}/_{oo}$, the colder water sinks, so that the flow is bi-directional. When the wall is tilted and the far-field salinity is greater than 25 $^{o}/_{oo}$, we observe a laminar upward flow under the wall which is driven by the salinity deficit, with a turbulent thermal convection beneath this layer.

During the past year, after redesigning and rebuilding his apparatus, Mr. Josberger observed the ablation and flow with three techniques. First, he froze thermistor arrays into his ice block, and then let them melt out during an experiment. By recording temperature and time of emergence, this technique yielded the wall temperature. Second, he took streak photographs of small particles within the flow which gave the flow velocities and direction within the boundary layer as well as the boundary layer thickness. Third, he used a precision transit to measure the rate of wall melting.

Theoretically, he has done a numerical model for the laminar flow case where the salinity is less than 24 $^{o}/_{oo}$ which predicts the observed wall temperature. He is presently working on a theoretical study for the turbulent flow case for salinities greater than 24 $^{o}/_{oo}$. This work has application to the prediction of pressure ridge keel lifetimes, and to the development of the fresh water surface layer in the summer Arctic. He presented a summary

of this work at the regional A.G.U. Conference in Victoria, B. C. on 1 October 1976.

2. Convective Processes in the Skeletal Layer of Young Sea Ice. A graduate student, Mr. Terren Niedrauer, is continuing his research under the supervision of S. Martin on the properties of the porous skeletal layer which occurs at the bottom of columnar sea ice. He is doing his experimental work within thin ice sheet tanks which are about 1 mm thick and have a depth and width of about 20 cm. These tanks are instrumented with small thermocouples and thermistors in order to correlate the temperature fluctuations within the ice sheet with the visually-observed velocity perturbations and brine channels.

Much of his effort during the past year has gone into rebuilding this apparatus. He has replaced the thermopane insulation on the box, which tended to reduce his photographic contrast, with a single layer of vacuum insulation. He has also redesigned the tank so that following an experiment, he can open the box, remove the thin ice sheet and analyze its salinity content. The experiment is now ready to run; we hope that it will yield data on the properties of the skeletal layer and on the formation of brine drainage features. Preliminary results from earlier experiments show that the sloping feeder channels associated with brine drainage systems lie at angles of 45° to the horizontal, whereas the temperature perturbation caused by the channels induces an isotherm tilt which is only of the order of 1-3°. He has also found that relatively small isotherm tilts appear to induce the growth of feeder channels into a central vertical channel. At the present time, he is organizing his observations both for comparison with existing field data and for publication in a report.

3. Ice Growth in a Wave Field. As part of our investigation of the growth of young sea ice, we built a wave tank measuring 2 m in length by 0.9 m in width which has a paddle at one end and can be filled with water to a depth of 0.4 m. This tank was built in part with BLM/NOAA funds in order to look at the dispersal of oil released under grease and pancake ice. For our ONR work, we are studying the physics of grease and pancake ice formation, also called frazil ice, and measuring the damping coefficient of the ice cover on the wave field.

In nature, ice growth in a wave field occurs at the edge of the polar ice pack and on leads and polynyas within the pack. The best observations on frazil ice growth comes from Ramseier's coring data from the joint U.S.-U.S.S.R. Bering Sea Experiment, which suggests that 10-30% of the ice on the Bering Sea is frazil ice. This ice forms in two regions in the Bering Sea. First, at the southern edge of the Bering Sea pack ice, ocean swell from the southwest propagates into the pack and causes frazil ice growth. Second, along both the Alaskan and Siberian coasts, the strong winds from the Northeast sweep the ice away from the land and generate wind waves, which also results in frazil ice growth. In the Beaufort Sea, the combination of cold winds and open water within leads and polynyas cause ice growth on wind waves. During a May field trip to the Beaufort Sea, S. Martin observed ice growth on a wind-generated wave field where the fetch was only 50 m.

During the present year, we have successfully grown both grease and pancake ice in the laboratory. We find when waves with lengths of order 0.5 m propagate through sea water at its freezing point, and this wave field is exposed to cold air, that grease ice forms in the tank. This grease ice consists of small platelet-shaped ice crystals, which are packed together in

a random manner with the result that water flows through the crystal mesh. By taking bulk samples of the ice, we find that the grease ice is a mixture of 35% ice crystals and 65% sea water. Therefore, as the ice mixture grows in thickness, its surface is always wetted and thus remains warm. When the air temperature was -20°C, we observed that the surface temperature ranged from -2° to -3°C, so that the heat transfer within the grease ice appeared to take place by the physical transport of the ice platelets which form at the surface down into the fluid. Our observations suggest that the ice thickness increases linearly and increases both in thickness and in the total amount of ice grown more rapidly than an ice sheet growing on still water.

As the ice-water mixture increases in thickness, the wave attenuation increases rapidly. For 80 mm of grease ice, we observe that waves of length less than 40 cm damp out completely before traveling 2 m. From such data we estimate the effective viscosity of the grease ice to be 10^3- 10^4 times that of sea water.

We also observe that when the grease ice thickness reaches about 100 mm that the ice surface starts to solidify into pancake ice, with the width of the pancake being of the order of one-fourth the driving wavelength. This pancake formation increases the wave damping, because of the change of the surface boundary from a viscous slurry to a solid plate. Also, the waves cause the pancakes to converge and diverge, so that grease ice rises into the cracks around the pancakes and heat is lost preferentially through the cracks and the grease ice continues to grow under the pancakes. Finally, as the pancakes grow in thickness, the wave damping continues to the point that the pancakes join together into larger floes and the grease ice ceases to grow so that the ice structure becomes columnar.

This work has application to the prediction of sea state in the marginal seas of the polar oceans, in the development of realistic models of heat transfer from the ocean to the atmosphere in these regions, and in predicting the acoustic properties of these ice fields.

INTERNAL WAVES

During the summer of 1975, internal wave observations were carried out adjacent to a moderate (10-12 meter) pressure ridge near the main AIDJEX camp. In general, conditions in the study area were unfavorable for internal wave generation, with weak currents and an anomalously deep and strong pycnocline. Late in July, when the pycnocline had moved up to a depth of 30 meters, stationary internal waves were observed on a number of occasions. The amplitude of these waves varied between 20 cm and 100 cm, with wavelengths between 30 m and 80 m. Examination of the current data revealed that in most cases these waves could not have come from the nearby pressure ridge, so calculations were carried out in an effort to determine whether these waves originated from a single feature upstream, or were the collective result of the general ridge distribution in the region. A model was constructed which calculates the internal wave field caused by a realistic pressure ridge distribution. The model, which covers a 10 x 10 km area, contains about 200 ridges with random spacings and orientations, but with an observed distribution of keel depths. The model has been run for a variety of current speeds and ridge distributions. Although analysis of the results is not yet complete, it appears that the observed waves are consistent with a distributed source, indicating that keel-generated waves may persist for many kilometers and contribute to the general internal wave spectrum in the

Arctic Ocean. It now appears that, except for brief periods when the current velocity is greater than 30-40 cm/sec, the overall internal wave drag on the ice will be small compared with the form drag. An effort will be made to use the model to determine regional values of wave drag as a function of current velocity. This work is being carried out by Mr. Fred Rigby, who is presently writing a Master's thesis on the subject. A paper describing these results will also be submitted to a journal for formal publication.

PRESSURE RIDGE MORPHOLOGY

We have long suspected that pressure ridge keels decay at much larger rates than does undeformed ice. This conclusion was reached on the basis of sketchy information on rates of ridge production, sonar profiles, diving reports and heat balance considerations, but no direct supporting evidence was available. During the summer of 1975, Fred Rigby and Arnie Hanson made growth rate measurements in two ridges near the main AIDJEX camp in an effort to settle this question. The primary study site was a first-year ridge some 10-12 meters in thickness which appears to have formed sometime during the preceeding fall - this was the same ridge used in the internal wave study described earlier. The second ridge was somewhat thinner and appeared to be old and solid. To define the shape and extent of the ridge keel, 38 holes were drilled both perpendicular to the ridge and along its longitudinal axis. Ten electric thickness gauges were installed in the young ridge and two in the older one. These gauges were read periodically throughout the summer to determine overall changes in the shape of the keel and to compare with the net mass changes measured at the thickness gauge sites. A few temperature profiles were also taken through the ridge. It had been hoped that we would

be able to monitor these ridges throughout an entire year, but the breakup and evacuation of the camp in the fall of 1975 precluded this possibility. Arnie Hanson, however, revisited the camp in April 1976 and was able to take a few temperature and thickness measurements, so we have some indication of the changes which took place during the winter.

The results support the notion that ridge keels undergo relatively rapid mass loss, but it is not clear to what extent this mass loss is controlled by thermodynamic processes. Most of the thickness curves show relatively rapid ablation rates, separated by step changes in thickness. At some sites there were thickness decreases in excess of 200 cm, as compared to about 30 cm under the level ice. The explanation for the step changes is the mechanical removal by currents of large ice blocks from the unconsolidated rubble which made up the lower part of the keel. Drilling records indicate that 5-10% of the young ridge consisted of water-filled cavities, presumably the spaces between rubble blocks; in the fall, these open spaces were replaced by soft or mushy zones, demonstrating that substantial freezing occurs within the ridge during the summer. Neglecting for the moment the step changes in thickness, ablation rates were at least double those under the level ice. However, it is again unclear whether this was due to an enhanced oceanic heat flux under the keels. The impression of the field personnel when drilling the ridge was that the lower part was "soft", so that the explanation of the larger ablation could be simply mechanical erosion of millimeter-sized pieces of ice, rather than melting. The spring observations indicated that there were surprisingly large thermal gradients in the keel and that there had been some accretion during the winter. We still feel, however, that ice growth under keels in excess of about 10 meters is generally negligible. These results

are presented in a paper, "The Evolution of a First-Year Arctic Pressure Ridge", which is scheduled to appear in the December 1976 AIDJEX Bulletin. A somewhat revised version will also be submitted to a formal journal.

The observations described above are a significant step forward in our understanding of processes associated with the large-scale heat and mass exchange near the surface of the Arctic Ocean. It now seems reasonably certain that ice from pressure ridge keels represents a major sink for short-wave radiation absorbed in the mixed layer. In the past, we have searched for mechanisms which would concentrate heat near the keels and cause enhanced melting there. While such mechanisms may exist, it now appears that the primary mechanism is the mechanical erosion which spreads pieces of the keel out over a large area where they can eventually melt without the necessity of a localized heat source. A quantitative treatment of the problem, however, will require additional information on keel evolution. In particular, we need to know what happens to deeper keels and how erosion of the more consolidated multiyear keels differs from that of the first-year keels. It is hoped that such questions will be addressed in future field experiments.

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1. Thorndike, A. S., D. A. Rothrock, G. A. Maykut and R. Colony, The thickness distribution of sea ice. Journal of Geophysical Research, 80, 4501-4513, 1975.

The polar oceans contain sea ice of many thicknesses ranging from open water to thick pressure ridges. Since many of the physical properties of the ice depend upon its thickness, it is natural to expect its large-scale geophysical properties to depend on the relative abundance of the various ice types. The ice pack is treated as a mixture whose constituents are determined by their thickness and whose composition is determined by the area covered by each constituent. A dimensionless function $g(h)$, the ice thickness distribution, is defined such that $g(h)dh$ is the fraction of a given area covered by ice of thickness greater than h but less than $h + dh$. A theory is developed to explain how the ice thickness distribution changes in response to thermal and mechanical forcing. The theory models the changes in thickness due to melting and freezing and the rearrangement of existing ice to form leads and pressure ridges. In its present form the model assumes as inputs a growth rate function and the velocity field of the ice pack. The model is tested using strain data derived from the positions of three simultaneous manned drifting stations in the central Arctic during the period 1962-1964 and growth rates inferred from climatological heat flux averages. The results are compared with estimates of g based on submarine measurements of ice thickness.

2. Maykut, Gary A., Energy exchange over young sea ice in the Central Arctic. AIDJEX Bulletin, 31, 45-74, 1976.

A simple model of heat transport in young sea ice is combined with climatological data on air temperatures and incoming radiation fluxes to predict how each component of the local heat balance in the Central Arctic is affected by the rapid growth of ice in leads. Results indicate that the net heat input to the atmosphere over 0-40 cm ice during the cold months is between one and two orders of magnitude larger than that over perennial ice. Once the ice exceeds about 100 cm in thickness, there is little change in any

of the heat fluxes as the ice thickens. Although both the amount of absorbed short-wave radiation and the emitted long-wave radiation depend on ice thickness, it is the turbulent fluxes which undergo the largest changes. The effects of a snow cover and variations in boundary layer temperatures are also examined. It is concluded that, with the present ice thickness distribution in the Central Arctic, total heat input to the atmospheric boundary layer from regions of young ice is equal to or greater than that from regions of open water or thick ice.

3. Rigby, F. A. and A. M. Hanson, The evolution of a large arctic pressure ridge. AIDJEX Bulletin, 34, (in press).

Extensive mass balance and structural observations were carried out on a large (10-12 m) pressure ridge during the summer of 1975 at the AIDJEX main camp. The authors drilled a large number of holes through the ridge and, by redrilling previously drilled areas and by monitoring thickness gauges, were able to examine ridge development over a period of several months. Some vertical temperature profiles were taken. The mass loss from the ridge bottom proved to be several times that from the undeformed ice, apparently resulting as much from mechanical erosion as from melting. The lateral extent of the keel was substantially greater than that of the sail and the pattern of isostatic compensation of the ridge changed with time.

4. Hall, R. T., G. A. Maykut, and D. A. Rothrock, Sea ice modeling: its testing with LANDSAT and potential use in FGGE. Proceedings of the Symposium on Meteorology 1976. Observations from Space (in press).

5. Martin, S. and P. Kauffman, An experimental and theoretical study of the turbulent convection generated under a horizontal ice sheet floating on warm salty water. Journal of Physical Oceanography (in press).

6. Grenfell, T. C. and G. A. Maykut, The optical properties of ice and snow in the Arctic Basin. Journal of Glaciology (submitted).

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